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The Modified Elastomagnetic Sensor Intended for a Quick Application on an Existing Prestressed Concrete Structures

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Abstract. The fully equipped elastomagnetic sensor is assembled from six basic components which are namely the sensor body, the primary coil, the secondary coil No. 1, the system of Hall probes, the secondary coil No. 2 and the steel shield of the sensor. Its additional installation on a tension steel element of an existing structure (as is typically a prestressed cable of a concrete bridge) involves the in situ process of the winding of its three coils that is relatively laborious and time-consuming. There is usually a large number of the tension elements on the investigated existing structure which should be investigated during the detailed construction inspection. The development of the modified elastomagnetic sensor that is described in this paper was based on an idea to reduce the laboriousness of the in situ process and also to obtain an effective tool for the quick detection and selection of which ones of the tension elements are most important for further detailed analysis and for installation of the fully equipped elastomagnetic sensors. In order to fulfil this idea, the modified elastomagnetic sensor was designed so that its each part can be easily mounted and then removed from the investigated tension element.

Introduction

In civil engineering practice, nowadays there are more often designed and built special engineering and building structures in which various structural elements are used that are loaded by large tensile forces as are, for example, internal or external cables of prestressed concrete bridges, stays of cable stayed bridges, hangers of arch bridges, suspension cables of suspended roofs, tensioning cables of tensile fabric membrane structures, ground and rock anchors. The forces in these elements, in many cases, significantly influence the reliability of the whole structure and they usually fluctuate considerably in time. Correct information about the actual force value is very important for accurate assessment of the structural reliability at any of the life cycle stages of the entire structure both during its construction or operational state.

There are also many similar existing structures with the same problem. The prestressed concrete bridges with internal cables or strands that are more than twenty years old form a special group. The knowledge of forces in internal prestressed reinforcements of these bridges, that is accurate enough, is important for thorough preparation of their reconstruction.

In civil engineering practice, five experimental techniques are generally used for determination of axial tensile forces in the important structural elements. The two of them (the direct measurement of the force by a pre-installed load cell and the approach based on a strain measurement with strain gauges) can be used only for evaluation of the total value of the tensile force in the observed structural elements during an experiment by which the applied sensors were installed before the elements were activated.

However, the next three of them (the vibration frequency method [1,2], the force determination in a flexible structural element based on the relation between the transverse force and the caused transverse displacement [3,4], and the magnetoelastic method [5–11]) are usable for new experiments on existing structures that are for some time already in service. It means that the observed structural elements remain activated during the experiment preparation, realization and also after the experiment completion.

The another advantages and disadvantages of all five mentioned techniques are discussed in more detail in the reference [8].

Motivation and objectives of the study

The fully equipped elastomagnetic sensor was introduced in detail in references [5,6]. It is assembled from six basic components that are the sensor body, the primary coil, the secondary coil 1, the system of Hall probes, the secondary coil 2 and the steel shield of the sensor.

The parts of the sensor body are printed on a 3D printer. The sensor proportions are always adapted to particular dimensions of a studied structural element. If the elastomagnetic sensor is to be installed on an already activated structural element on an existing structure, its body is consequently assembled, in a relatively easy way, on the element during preparation phase of the experiment.

However, the subsequent steps of the elastomagnetic sensor production procedure involves the in situ process of the winding of the three coils that is relatively laborious and time-consuming which last for about three hours in relatively comfortable conditions.

Moreover, there is usually a large number of the structural elements on the investigated existing structure (prestressed cables or strands on a prestressed concrete bridge, for example) which should be potentially investigated during the detailed construction inspection.

The fundamental motivation for the development of the modified elastomagnetic sensor that is described in this paper was based on an idea to reduce the laboriousness of the in situ production process.

The next reason for the research was to obtain also an effective tool for the quick detection and selection of which ones of the studied structural elements are most important for further detailed analysis and for installation of the fully equipped elastomagnetic sensors. For example, it means to select the elements with the smallest or largest axial tensile force.

In order to fulfil these ideas, the modified elastomagnetic sensor was designed so that its each part can be easily mounted and then removed from the investigated structural element and that no one coil has to be winded in situ.

The brief description of the developed elastomagnetic sensor

Two variants of the removable elastomagnetic sensor (see Fig. 1) were developed and studied to fulfil the above mentioned motivation and objectives of the study.

The first variant of the removable sensor (see Fig. 1) applies two permanent neodymium magnets as the source of variable magnetic field. The parameters of the magnetic field are then measured using four Hall probes. The sensor consists of two basic parts. The first one is intended for attachment to the investigated structural element (see Fig. 2) by four disposable cable ties (see Fig. 1) and the second part is the moving one (see Fig. 2).

The four Hall probes are fixed in the first stationary part of the sensor. Two Hall probes are situated in its centre (see Fig. 2) and they measure the properties of magnetic field in a direction parallel with the element axis. The next two Hall probes are located on axes of the magnets (see Fig. 2) and they monitor the magnetic field properties in a direction perpendicular to the element axis.

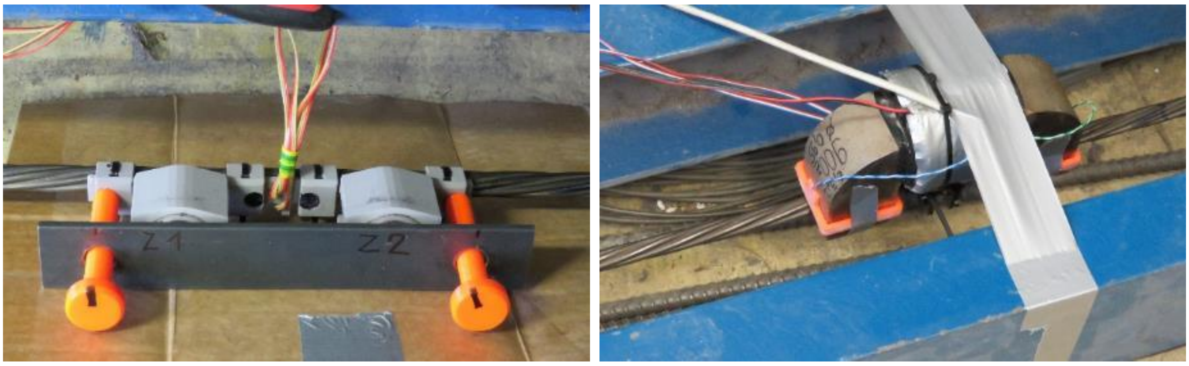

Fig. 1: Two studied variants of the removable modified elastomagnetic sensor with two permanent neodymium magnets (on left) and with the portable primary coil (on right) which are installed on the prestressed strand

Fig. 2: The first studied variant of the removable modified elastomagnetic sensor – the sensor part intended for attachment to the element (on left) and the moving part with two permanent neodymium magnets (on right)

The second moving part of the sensor includes two permanent neodymium magnets and it can move in the direction perpendicular to the investigated element and in this way can change the magnetic field. The movement is controlled by two orange screws (see Fig. 1 and Fig. 2) in the case of the applied primary prototype of the sensor.

The second variant of the removable sensor (see Fig. 1) applies a portable primary coil wrapped around a steel horseshoe-shaped core (see Fig. 3) for developing sufficiently intense variable electromagnetic field. The parameters of the magnetic field are measured applying two pole secondary coils and two Hall probes. The pole secondary coils are winded in orange cases that are put on the both ends of the steel core (see Fig. 1 and Fig. 3) and they measure the magnetic field properties in a direction perpendicular to the element axis.

The two Hall probes (see Fig. 3) are fixed in a black holder that is mounted on the studied structural element so that the Hall probes are situated in the centre plane of the sensor perpendicular to the element (see Fig. 2 and Fig. 3) and they measure the properties of magnetic field in a direction parallel with the element axis.

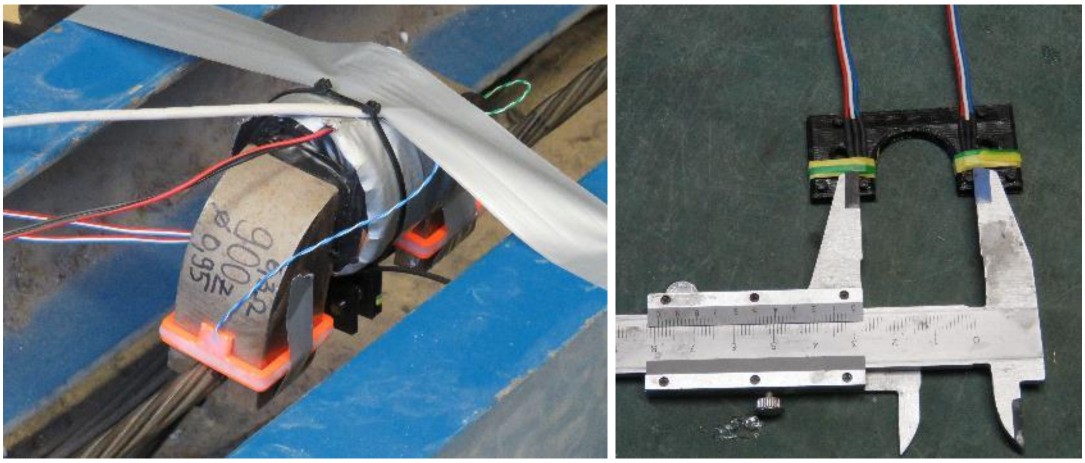

Fig. 3: The second studied variant of the removable modified elastomagnetic sensor – the steel horseshoe-shaped core with the wrapped primary coil and the pole secondary coil put on it (on left) and two Hall probes fixed in the part of their holder (on right)

The description of the experiment arrangement

The both variants of the removable sensor were verified by practically identical experiments (see Fig. 4). A prestressed strand was fastened in a steel test frame and next the particular variant of the removable sensor was attached to the strand. Then a calibrated hollow hydraulic jack was used to apply the tension force into the strand in several force steps and simultaneously the influence of the mechanical stress to the magnetoelastic characteristics of the prestressed strands were observed and evaluated.

Fig. 4: View of arrangement of the experiments with the hollow hydraulic jack, the steel test frame, the fastened prestressed strand and the first variant of the removable elastomagnetic sensors attached to the strand (on left) and the second one (on right)

The obtained results

During the results evaluation, the experiments based on the modified magnetoelastic method, which is described in more details in references [5–8], apply usually measured hysteresis loops, that include also their sections with the technical saturation points. This procedure allows to realize experiments independently on application of particular elastomagnetic sensors or other devices.

For a deeper understanding of relationships, the both developed variants of the removable sensor were also analysed theoretically. Two created theoretical models were built in the software Ansys Maxwell 3D (see Fig. 6, Fig. 9 and Fig. 10) and they both correspond to the real arrangement and conditions of the both experiments.

The default boundary conditions that are available in Ansys Maxwell 3D software were used on boundaries of the resolved regions for both theoretical models. And the flux normal conditions were, of course, applied on the plane of symmetry. The resolved regions were about three times larger than investigated sensors in each dimension. Likewise, the default parameters of the material applied in the models were adopted from the software material library. Namely, the ferromagnetic „Steel_1010“ was used as a strand material. Suitability of this material and its properties for the purpose of the realized theoretical analysis was verified in the course of some former authors’ works [5,6].

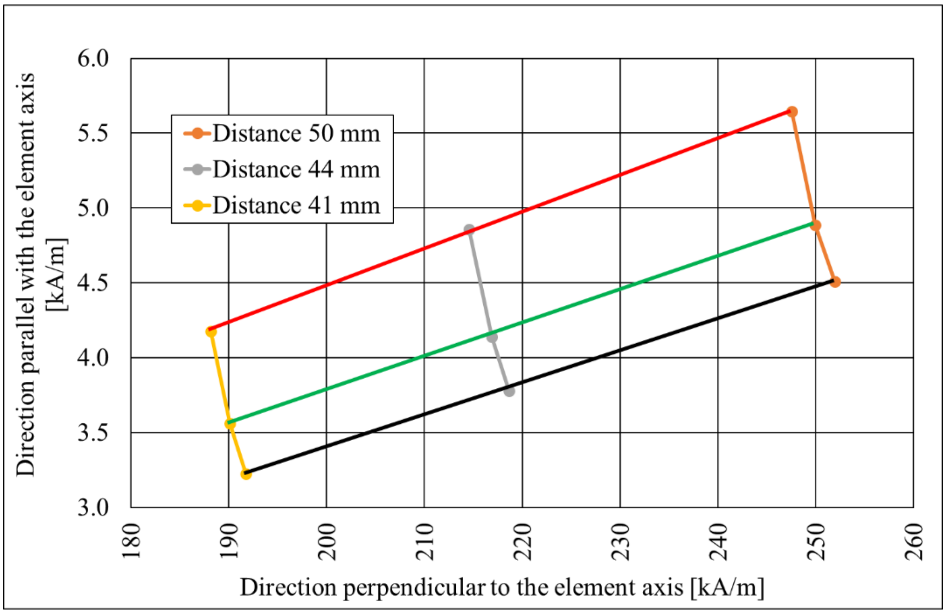

Fig. 5: The results obtained by application of the first studied variant of the removable modified elastomagnetic sensor – the dependence between measured values of the magnetic field intensity "H" for three tension force steps and three magnet positions

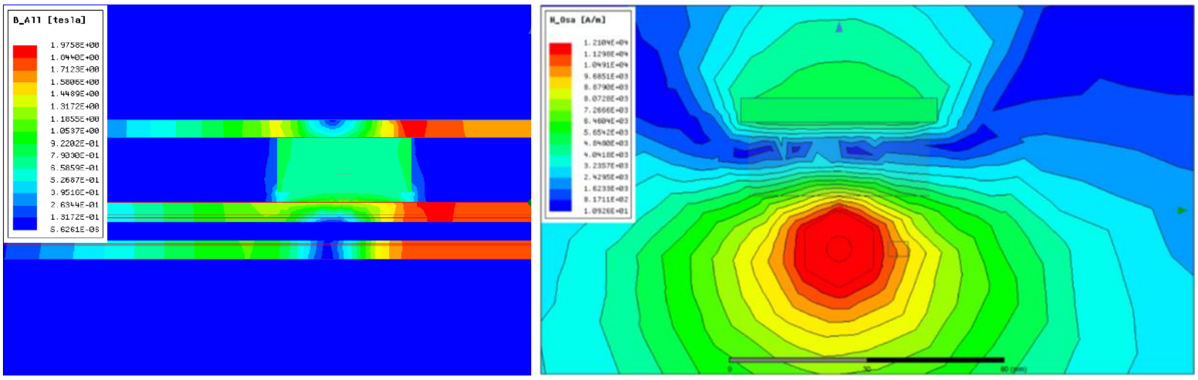

Fig. 6: The magnetic induction field "B" (on left) and the magnetic field intensity “H” (on right) determined on the theoretical model of the first variant of the sensor (the variant with two permanent neodymium magnets) installed on the studied prestressed strand

The experimental results obtained by application of the first variant of the removable elastomagnetic sensor (the variant with two permanent neodymium magnets) show that there is an applicable dependence between measured parameters of the magnetic field and the value of tension force in the strand as is demonstrated in Fig. 5.

The dependence between values of the magnetic field intensity "H" measured by the Hall probes for three tension force steps and three magnet positions relative to the strand is depicted in Fig. 5 where the "H" values, which were measured in the direction perpendicular to the strand axis in the points located on axes of the magnets, are plotted on the horizontal axis and the "H" values, which were measured in the direction parallel with the strand axis in the sensor centre, are plotted on the vertical axis.

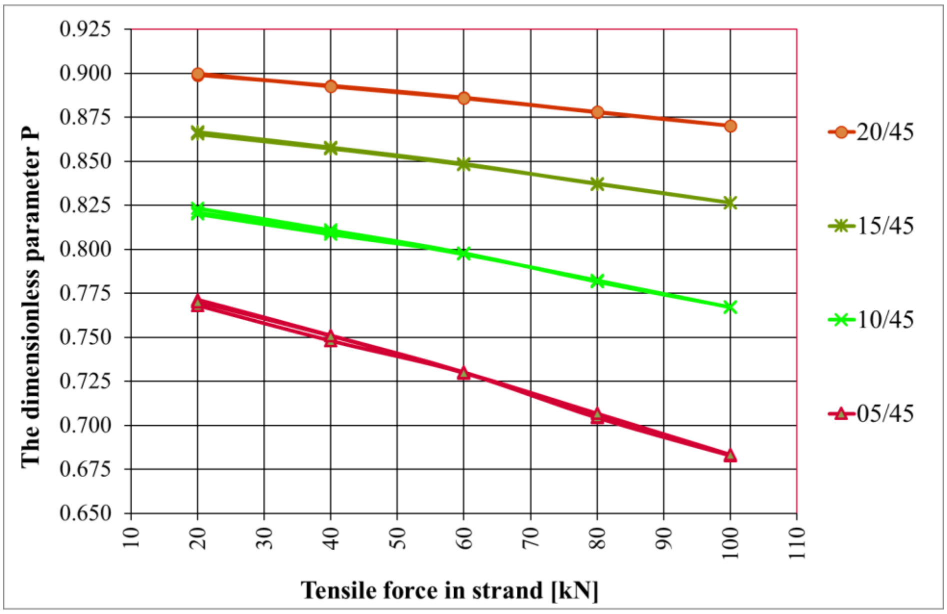

Fig. 7: The results obtained by application of the second studied variant of the removable modified elastomagnetic sensor - comparison of the different resultant dimensionless parameter P

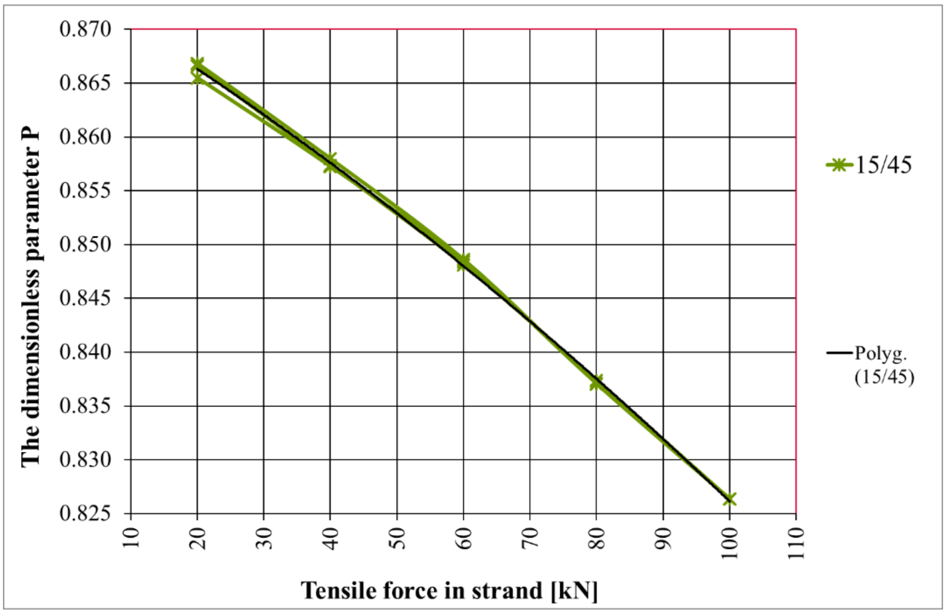

Fig. 8: The results obtained by application of the second studied variant of the removable modified elastomagnetic sensor - the relation between the tensile force in the observed strand and the chosen resultant dimensionless parameter P 15/45

The three lines in Fig. 5 (the red, green and black one) correspond to three specific set values of tensile force in the strand. The red line is related to the force 100 kN, the green line to 60 kN and the black one to 20 kN.

However, the required state of the studied strand, when its technical saturation would be reached in its central section, was not achieved. Moreover, the theoretical analysis revealed that this state could not be also obtained by the application of stronger neodymium magnets in the course of the experiment.

In the course of the application of the second variant of the removable elastomagnetic sensor (the variant with the portable primary coil) the required state of the studied strand with its technical saturation was achieved. The experimental results revealed that the second sensor variant can be used for the intended purpose to select quickly which tension elements are most important for further detailed analysis. However, the precision of the gained results is lower than for the fully equipped elastomagnetic sensors.

The influence of the defined stress in the investigated strand on the parameters of the magnetic field was studied for five steps of the tension force that were 20 kN, 40 kN, 60 kN, 80 kN and 100 kN. For each used force step, the hysteresis loop was measured and determined, results presented in Fig. 7 were evaluated based on the experimental data about magnetic field intensity "H" measured by two applied Hall probes located in the centre plane of the sensor and about magnetic induction “B” monitored by the two pole secondary coils.

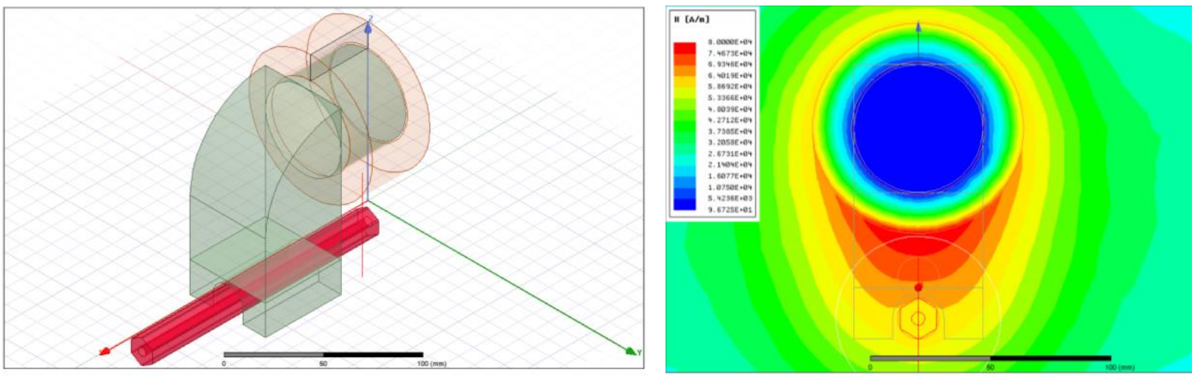

Fig. 9: The view of the theoretical model of the second sensor variant installed on the studied strand (on left) and the magnetic field intensity “H” calculated on this model (on right)

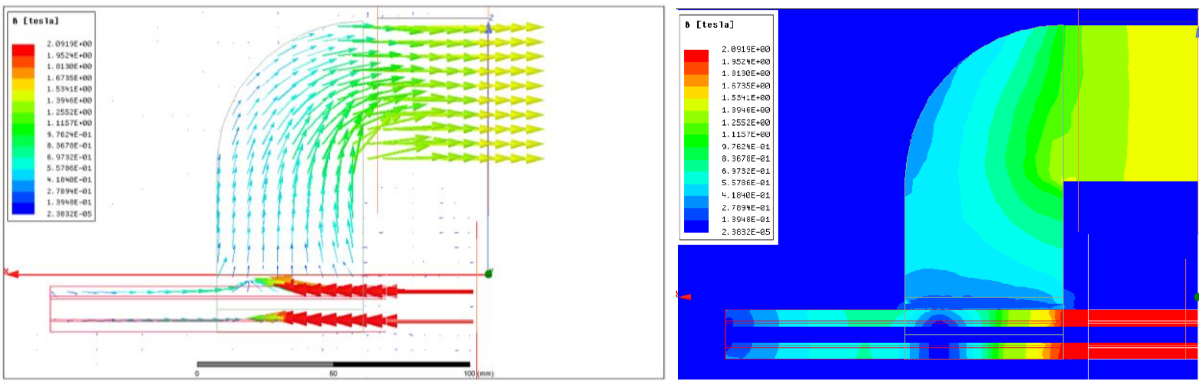

Fig. 10: The magnetic induction field "B" determined on the theoretical model of the second variant of the sensor – the vectors in the longitudinal plane of symmetry (on left) and intensity (on right)

The dimensionless parameter P, that is shown for the realized experiment in Fig. 7, is standardly evaluated for the purpose of a practical application of the modified magnetoelastic method [5,7,8]. It is used to convert a complex measured shape of the hysteresis loop, that depends on the actual force magnitude, to one simple numeric value. The fractions in Fig. 7 describe points of the hysteresis loop taken into account as the key node points for the conversion of the loop shape to the particular parameter P. The numerator of the fractions is the most important value for evaluation of the parameter P indicating the level of the magnetic field intensity "H" in the main node point. The lower values of this indicator indicate the preference of the portion of the hysteresis loop close to the remanence (the intersection with the vertical axis in the B–H curve). On the contrary, its higher values prefer the loop portion near to the saturation. The more exact definition of the parameter P is an industrial secret.

During the realized verification experiment using the second sensor variant, four various dimensionless parameters P were evaluated that represented in a simple way the character and shape of measured hysteresis loops. The sensitivity of the evaluated parameters P to the tension force was studied (see Fig. 7). For advance analysis, the parameter P “15/45” was chosen as the most suitable one because of its sufficient sensitivity and satisfactory stability of obtained results.

For the chosen parameter P “15/45” the detailed analysis of its sensitivity to the tensile force in the studied strand was realized, the results of this analysis are shown in Fig. 8. The resultant regression fitting curve (the black curve in Fig. 8) was determined using methods of mathematical analysis and statistics.

Conclusions

The fundamental results of two verification experiments that were focused on application of two variants of the removable elastomagnetic sensor are described in this paper.

The published results show that the both variants of the removable sensor can be used for a relatively quick experiment intended for the evaluation of the total value of the tensile force in the structural elements activated before the start of the experiment.

However, the second variant of the modified elastomagnetic sensor (the variant with the portable primary coil) is more suitable for this purpose than the first one. Most particularly because, the required state of the studied strand with its technical saturation, that is important for experiments realized using the modified magnetoelastic method, can be achieved applying the second variant of the sensor only.

As it was expected at the beginning of the investigation, the precision of the results obtained by application of the second sensor variant is distinctly lower than for the fully equipped elastomagnetic sensors.

On the other hand, the experimental results revealed that the second sensor variant can be used for the intended purpose to select quickly with sufficient accuracy which tension elements from their group are most important for further detailed analysis and so for installation of the fully equipped elastomagnetic sensor.

The utilization of the both removable and fully equipped modified elastomagnetic sensor is suitable especially for applications on structural elements with short free length, as are, for example, the prestressed cables permanently embedded in the monolithic concrete construction, that are exposed for the purpose of the experiment to the minimum necessary length. For structural elements with a long free length, the other methods mentioned above in this paper can be applied more effectively.

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References

[1] M. Polák, T. Plachý, Determination of Forces in Roof Cables at Administrative Center Amazon Court, Procedia Engineer. 48, (2012) 578-582.

[2] M. Polák, T. Plachý, Experimental Evaluation of Tensile Forces in Short Steel Rods, Appl. Mech. Mater. 732, (2015) 333-336.

[3] P. Fajman, M. Polák, Measurement of structural cable of membranes, in: Proceedings of the 50th Annual Conference on Experimental Stress Analysis, EAN 2012, Tábor, Czech Republic, 2012, pp. 61-64.

[4] P. Fajman, M. Polák, J. Máca, T. Plachý, The Experimental Observation of the Prestress Forces in the Structural Elements of a Tension Fabric Structure, Appl. Mech. Mater. 486 (2014) 189-194.

[5] T. Klier, T. Míčka, M. Polák, T. Plachý, M. Hedbávný, L. Krejčíková, New Information about Practical Application of the Modified Magnetoelastic Method, MATEC Web Conf. 310 (2020) 00026.

[6] T. Klier, T. Míčka, M. Polák, T. Plachý, M. Hedbávný, R. Jelínek, F. Bláha, Application of the Modified Magnetoelastic Method and an Analysis of the Magnetic Field, Acta Polytechnica CTU Proceedings 15 (2018) 46-50.

[7] T. Klier, T. Míčka, T. Plachý, M. Polák, T. Smeták, M. Šimler, The verification of a new approach to the experimental estimation of tensile forces in prestressed structural elements by method based on the magnetoelastic principle, MATEC Web Conf. 107 (2017) 00015.

[8] T. Klier, T. Míčka, M. Polák, T. Plachý, M. Šimler, T. Smeták, The in Situ Application of a New Approach to Experimental Estimation of Tensile Forces in Prestressed Structural Elements by Method Based on the Magnetoelastic Principle, in: Proceedings of the 55th Conference on Experimental Stress Analysis 2017, Košice, Slovakia, 2017, pp. 122-132.

[9] M. Chandoga, P. Fabo, A. Jaroševič, Measurement of Forces in the Cable Stays of the Apollo Bridge, in: Proceedings of the 2nd fib Congress, Naples, Italy, 2006, pp. 674-675.

[10] A. M. Sarmento, A. Lage, E. Caetano, J. Figueiras, Stress measurement and material defect detection in steel strands by magneto elastic effect. Comparison with other non-destructive measurement techniques, in: Proceedings of the 6th International Conference on Bridge Maintenance, Safety and Management IABMAS 2012, Stresa, Lake Maggiore, Italy, 2012, pp. 914-921.

[11] H. J. Wichmann, A. Holst, H. Budelmann, Magnetoelastic stress measurement and material defect detection in prestressed tendons using coil sensors, in: Proceedings of 7th International Symposium on Non-Destructive Testing in Civil Engineering NDTCE’09, Nantes, France, 2009.